This Topic covers a range of key technology options associated with future space exploration systems and architectures that are 'energy rich'-including high power space systems, highly efficient and reliable space propulsion systems, and the storage, management, and transfer of energy/propellants in space. It also addresses high-energy maneuvering including aero-entry, aero-braking, and other aero-assist related R&D. The affordable deployment of systems and logistics beyond low Earth orbit will depend on high-power space transportation. In addition, a broad range of future systems and technologies will be constrained or enabled by the availability (or lack) of significant power at an affordable cost.

Subtopics

X7.01 Chemical Propulsion Systems and Modeling

Lead Center: MSFC
Participating Center(s): AFRC, GRC

The goal of this subtopic is to develop innovative chemical propulsion systems and system concepts as well as modeling tools and capabilities that support chemical propulsion system design and analysis. Applications of interest include earth-to-orbit and in-space transportation, with a particular focus on versatile, multi-use in-space cryogenic engines with exceptionally high reliability, space-based reusability (i.e. capability for many restarts with little to no maintenance), and deep-throttling capability. These are needed for all phases of exploration missions, including trans-lunar injection, decent to the lunar surface, ascent to lunar orbit, and return to Earth. Also of interest are safe and affordable earth-to-orbit systems that enable high overall vehicle payload mass-to-liftoff mass ratios, with improvements in thrust-to-engine weight ratio, trajectory-averaged specific impulse, and overall reliability.

Specific areas of interest for technology advancement and innovations include:

- Propulsion system design concepts that address LOX/LH$_2$, as well as LOX/CH$_4$ and other LOX/Hydrocarbon engine and main propulsion systems integration issues;
• Integrated chemical propulsion system concepts that integrate primary propulsion and reaction control system elements;

• Design and analysis tools that significantly enhance the overall systems engineering evaluation of advanced chemical propulsion system concepts. These include tools for sensitivity analysis, quantification of system benefits to changes, propulsion system operability, "bottoms up" weight estimating, cost estimating, and reliability prediction for propulsion systems;

• Manufacturing techniques that allow for significant reduction in the cost and schedule required to fabricate engine and main propulsion system components. These techniques can use current or emerging processes and manufacturing technologies to develop engine and main propulsion system components that will reduce complexity, increase reliability, and that are easier to assemble, install, and test when integrated onto the vehicle;

• Concepts for solid or hybrid rockets that increase mass fraction, decrease the need for thermal insulation, and reduce or eliminate the need for staging; and

• High-performance advanced propellants (as indicated by high specific impulse and high specific impulse density) and non-toxic propellants that can significantly improve safety and cost of propulsion systems operations.

Note: Related technologies of interest but covered under other SBIR subtopics include:

• X7.02 Chemical Propulsion Components

• X8.01 Vehicle Health Management Systems

X7.02 Chemical Propulsion Components

Lead Center: MSFC

Participating Center(s): GRC, JSC

The goal of this subtopic is to develop innovative chemical propulsion component technologies that improve the safety, operability, reliability, and performance of propulsion systems required for human and robotic exploration missions. Components should be applicable to earth-to-orbit or long-duration in-space transportation systems (both primary propulsion and reaction control systems) for a variety of exploration mission phases, including trans-lunar injection, decent to the lunar surface, ascent to lunar orbit, and return to Earth.

System masses will be critical in these far-reaching missions, dictating the use of lightweight components and the use of propellants harvested or manufactured on the surface of the Moon, Mars, or other destinations-an approach known as in situ resource utilization (ISRU). Candidate ISRU propellants include hydrogen, oxygen, carbon monoxide, carbon dioxide, methane, various other hydrocarbons, and compounds derived from these materials.
In some scenarios, one propellant may be manufactured \textit{in situ} while its oxidizer or fuel is brought from Earth. Because the use of ISRU propellants represents a departure from the state-of-the-art and from the existing base of engines and technologies, a new suite of propulsion system and component technologies will be required.

These new in-space propulsion systems are expected to encounter conventional challenges such as regulator leakage, valve leakage, valve heating (on pulsing engines), solubility effects (such as combustion instabilities caused by gas bubble evolution in liquid propellants), and propellant acquisition (i.e., extracting gas-free propellant from the tank and delivering it to the engine). In-space chemical propulsion systems that incorporate long-term use of cryogenic propellants such as hydrogen, methane and oxygen present new challenges, including efficient, reliable, and durable propellant cryocooling, storage, acquisition (from tanks), transfer (through feed lines), gauging and flow measurement; however, these particular challenges are addressed by a separate sub-topic, X3.03 Cryo and Thermal Management.

Chemical propulsion component technologies that demonstrate improved capabilities using a variety of propellant combinations are of interest, including:

- Advanced turbopumps with wider throttle range and improved cavitation control, plus specific turbomachinery components such as bearings, turbines, and impellers that demonstrate greater reliability and lifetime;
- Injectors with low thermal mass and long-duration reliability (e.g. for high duty-cycle attitude control thrusters);
- Long-life combustion chambers (e.g., based on use of advanced materials);
- Innovative thruster valve designs that tolerate high thermal loading due to heat soak-back during pulse mode operation;
- Innovative concepts for fast acting valves to enable use of larger thrusters for small impulses (i.e. spacecraft fine pointing);
- Highly-reliable long-duration seals;
- Long-life, high-reliability ignition systems;
- Lightweight, highly reliable gas compressors for pumping gaseous propellant into pressure vessels either in-flight or on a terrestrial surface;
- Novel pressurization approaches that minimize dissolution of pressurant gas in storable propellants (e.g., nitrogen tetroxide, hydrazine, and hydrazine derivatives)
- Novel concepts that increase performance or decrease mass of pressurization systems;
- Development of advanced materials that exhibit high compatibility with gaseous oxygen;
- Propulsion components based on microelectromechanical systems (MEMS) technology;
- Advanced nozzle concepts for in-space propulsion systems;
- Reaction control system thrusters that burn \textit{in situ} and non-toxic propellants;
Innovative thruster designs that minimize or prevent high heat soak-back during pulse mode operation;
Highly reliable, lightweight compressors for use in gaseous propellant storage and distribution systems;
Advanced lightweight multi-use positive expulsion devices for storable propulsion systems; and
Other innovative chemical propulsion system components that improve system safety, affordability, or effectiveness.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- X3.03 Cryo and Thermal Management
- X7.01 Chemical Propulsion Systems and Modeling
- X8.01 Vehicle Health Management Systems

X7.03 High-Power Electric Propulsion

Lead Center: GRC
Participating Center(s): JPL, JSC

The goal of this subtopic is to develop innovations in high-power (100 kW to MW-class) electric propulsion systems. High-power (high-thrust) electric propulsion may enable dramatic mass and cost savings for lunar and Mars cargo missions, including Earth escape and near-Earth space maneuvers. At very high power levels, electric propulsion may enable piloted exploration missions as well. Improved performance of propulsion systems that are integrated with associated power and thermal management systems and that exhibit minimal adverse spacecraft-thruster interaction effects are of interest. Innovations are sought that increase system efficiency, increase system and/or component life, increase system and/or component durability, reduce system and/or component mass, reduce system complexity, reduce development issues, or provide other definable benefits. Desired specific impulses range from a value of 2000 s for Earth-orbit transfers to over 6000 s for planetary missions. System efficiencies in excess of 50% and system lifetimes of at least 5 years are desired. Specific technologies of interest in addressing these challenges include:

- Long-life, high-current cathodes (100,000 hours);
- Electric propulsion designs employing fuels that are more readily available (whether from Earth or in situ space resources) and easy to store/handle;
- Electrode thermal management technologies;
• Innovative plasma neutralization concepts;
• Metal propellant management systems and components;
• Cathodes for metal propellants;
• Low-mass, high-efficiency power electronics for RF and DC discharges;
• Lightweight, low-cost, high-efficiency power processing units;
• Low-voltage, high-temperature wire for electromagnets;
• High-temperature permanent magnets and/or electromagnets;
• Application of advanced materials for electrodes and wiring;
• Highly accurate propellant control devices/schemes;
• Miniature propellant flow meters;
• Lightweight, long-life storage systems for krypton and/or hydrogen;
• Fast-acting, very long-life valves and switches for pulsed inductive thrusters;
• Superconducting magnets;
• Lightweight thrust vector control for high-power thrusters; and
• High fidelity methods of determining the thrust of ion, Hall, and advanced plasma engines without using conventional thrust-stands.

Note: Related technologies of interest but covered under other SBIR subtopics include:

• Low- to medium-power solar electric propulsion for planetary science missions (S8.04 Spacecraft Propulsion).

X7.04 Aeroassist Systems

Lead Center: JSC
Participating Center(s): AFRC, ARC, LaRC

The goal of this subtopic is to develop innovative human-rated aeroassist systems for missions including lunar return to Earth and precursor missions for human Mars exploration. Systems are needed to support the following flight regimes: aerocapture, entry interface to subsonic speeds, and Mach 5 to subsonic speeds. Systems must be capable of controlled flight and be compatible with pinpoint, soft landing systems, which achieve landing accuracies of 10s of meters at touchdown or powered descent initiation. These systems must be compatible with launch vehicles and transit vehicles and capable of safely discarding unneeded and constraining hardware on landing and
providing surface access. Technology needs include aeroassist system design, Thermal Protection System (TPS) designs, modeling capabilities, sensor systems, and navigation technologies that support reliable aerocapture or aerobraking of multi-metric-ton-class piloted or cargo spacecraft. In particular, this subtopic seeks innovations in the following areas:

- Innovative aeroassist system designs. This includes low-mass, rigid aeroassist systems based on robust, high-temperature structures and adhesives, modular or deployable/inflatable aeroshells with large surface area, and inflatable ballutes;

- TPS designs for human-rated aeroassist vehicles returning to Earth from the Moon and Mars, and for Mars aerocapture and Entry, Descent and Landing (EDL). Innovative TPS concepts are solicited to reduce current TPS mass fractions by 25% to 50% and to reduce TPS costs;

- Ablative and reusable TPS materials and concepts that significantly enhance performance and reduce mass. This includes development and characterization of single- and multi-use TPS materials, TPS for rigid aeroshells, and flexible TPS materials for deployable aeroshells. Thermo-chemical and mechanical properties data for probabilistic design, spallation characteristics, and accurate simulation tools to predict material behaviors and material compatibility are required. Innovative TPS concepts are solicited to reduce current TPS mass fractions by 25% to 50% and to reduce TPS costs;

- Aerothermodynamic modeling tools with greater accuracy and less uncertainty: (1) Innovative and accurate computer modeling of fluid structure interactions, including flow stability and surface deflections under dynamic conditions for decelerator deployment and inflation; (2) Modeling and simulation of convection/radiation/ablation coupled three-dimensional flow fields, for both optically thick and thin shock layers and highly ionized flows; (3) Accurate prediction of wake heating including radiative heating components; (4) Accurate prediction of single and multiple rocket plume effects (e.g., reaction control system thrusters) on the vehicle aerodynamics and heating;

- Innovative sensor systems which are capable of providing real-time or near real-time updates to atmospheric pressure, temperature, density, and winds to support the guidance systems used on aeroassist vehicles;

- Innovative sensor systems for inflatable aeroassist vehicles capable of providing real time aerosurface temperature, strain, deflection, flight loads and other significant parameters; and

- Lightweight flexible materials that will reduce the mass and increase the strength and thermal characteristics for applications to deployable aeroshells and supersonic deployed decelerators.

Focus should be on aeroassist systems applied to the following mission classes:

- **Earth return of piloted spacecraft from the Moon.** Return-to-Earth scenarios for human lunar missions include: (1) short-range direct entry and landing; (2) extended-range entry using a skip out of the atmosphere with subsequent EDL to the Earth's surface; and (3) aerocapture into a low-energy Earth orbit followed by EDL. Inertial arrival speeds of approximately 11 km/s (up to 12 km/s for some abort scenarios) with entry masses of at least 5 metric tons are expected for normal lunar return. Acceptable sustained loads for these piloted missions are limited to about 5 gs perpendicular to the human spine in the "eye balls in" direction; and

- **Mars precursor missions for human exploration.** These include robotic missions designed to deliver pre-deployed cargo or to conduct technology demonstrations in anticipation of follow-on human Mars missions.
Candidate human mission scenarios for Mars include human and cargo aerocapture into a Mars orbit followed by EDL to the Mars surface and return to Earth. Mars aerocapture missions are expected to have arrival speeds of 6 to 8 km/s and aerocapture mass on the order of many 10s of metric tons. Return-to-Earth scenarios for human Mars missions are similar to those for lunar missions, except for higher arrival speeds (11.5 - 12.5 km/s, up to 14 km/s for some off-nominal scenarios).

Note: Related technologies of interest but covered under other SBIR subtopics include:

- Inflatable and other innovative structures (X2.02 Structures and Habitats); and
- Aeroassist systems for deep space robotic science missions (S5.01 Low Thrust and Propellantless Propulsion Technologies).